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THE RELATIONSHIP BETWEEN TENSILE STRENGTH AND FLEXURE STRENGTH --ETC(U)
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THE RELATIONSHIP BETWEEN TENSILE STRENGTH AND FLEXURE STRENGTH IN FIBER REINFORCED COMPOSITES

James M. Whitney
Marvin Knight

Mechanics and Surface Interactions Branch
Nonmetallic Materials Division

December 1980

TECHNICAL REPORT AFWAL-TR-80-4104

Interim Report for Period 15 January 1979 - 15 August 1979

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AFWAL-TR-80-4104	2. GOVT ACCESSION NO.: AD-A097033
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): THE RELATIONSHIP BETWEEN TENSILE STRENGTH AND FLEXURE STRENGTH IN FIBER REINFORCED COMPOSITES.	5. TYPE OF REPORT & PERIOD COVERED: 15 Jan 79 - 15 Aug 79
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): James M. Whitney, Marvin Knight	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Materials Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson AFB, Ohio 45433	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 241903, 24190310
11. CONTROLLING OFFICE NAME AND ADDRESS: Materials Laboratory, AFWAL, Air Force Systems Command, Wright-Patterson AFB, Ohio 45433	12. REPORT DATE: December 1980
	13. NUMBER OF PAGES: 45
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Tensile strength
Flexure strength
Composite materials
Unidirectional composite
Weibull distribution

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Tensile data on unidirectional composites generated from a flexural test usually yield a higher strength than observed from a standard tensile coupon. According to a statistical strength theory based on a Weibull distribution, the presence of a stress gradient in the flexure test results in an apparent increase in tensile strength as compared to the tensile test under uniform stress. In the present paper this concept is explored by utilizing data from unidirectional graphite-epoxy composite to compare with theoretical results generated from a two parameter Weibull distribution. A larger variation in

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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tensile strength is observed from tensile coupon data than from flexure data. Such differences are not in accordance with strength theories based on a uniform flaw distribution and raise questions concerning variability of the test methods, as well as sources of material variability.

AFWAL-TR-80-4104

FOREWORD

In this report, flexure and tensile coupon data on unidirectional graphite-epoxy composites are compared to a Weibull two parameter statistical strength model.

This report was prepared in the Mechanics and Surface Interactions Branch (AFWAL/MLBM), Nonmetallic Materials Division of the Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. The work was performed under Project 2419, "Nonmetallic Structural Materials," Task No. 241903, "Composite Materials and Mechanics Technology." The time period covered by this effort was from 15 January 1979 to 15 August 1979. James M. Whitney and Marvin Knight (AFWAL/MLBM) were the laboratory project engineers.

Experimental data discussed in this report was obtained by the University of Dayton Research Institute under Air Force Contract AF33615-78-C-5102.

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SECTION I

INTRODUCTION

Tensile data on unidirectional composites are often used as one of the key factors in materials selection, and also provides basic ply properties which are used in laminate design. Such data generated from a unidirectional flexure test usually yield higher strength than data obtained from a standard tensile coupon. It is primarily for this reason that flexure data is not considered appropriate for design purposes. This difference in apparent tensile strengths can be accounted for, however, if one considers the brittle nature of most polymeric matrix composites. In particular, a statistical strength theory based on a Weibull distribution (Reference 1) can be used to explain the difference between unidirectional tensile data generated from a flexure test and a standard tensile coupon. The presence of a stress gradient in the flexure test results in an apparent increase in tensile strength compared to the tensile test under uniform stress. Establishment of a viable relationship between the flexure test and standard tensile coupon test would provide a potential basis for use of the flexure test in the generation of unidirectional design data. Since flexure tests are easy to run and relatively inexpensive, a large statistical data base obtained with this method rather than tensile coupons is far more economical.

A two-parameter Weibull model was used by Bullock (Reference 2) in correlating 4-point flexure and tensile coupon data for unidirectional graphite-epoxy composites. Excellent agreement was obtained between theory and experiment. The Weibull model has been previously applied to ceramic materials (References 3, 4) and more recently to randomly oriented short fiber composites (Reference 5).

In the present work, unidirectional graphite-epoxy tensile data are obtained on both 3-point and 4-point flexure tests as well as on straight-sided tensile coupons. The influence of specimen thickness on tensile strength is investigated in addition to the effect of stress gradient. Thus, a much broader data base for comparison to Weibull statistical theory is available in the current work than presented by

Bullock (Reference 2). Unlike the experimental results discussed in Reference 2, a significantly larger variation in tensile strength versus flexure strength is obtained with the current data. This trend is observed in two entirely different graphite-epoxy material systems. Such differences are not in accordance with statistical strength theories based on a uniform flaw distribution. Possible sources of this departure from classical brittle failure theory are discussed in detail.

SECTION II

STATISTICAL STRENGTH MODEL

According to the Weibull statistical strength theory for brittle materials (Reference 1), the probability of survival, P, at a maximum stress level S for a uniaxial stress field in a homogeneous material governed by a volumetric flaw distribution is given by

$$P(S_f \geq S) = R(S) = \exp[-B(S)] \tag{1}$$

where S_f is the value of the maximum stress at failure and B is the risk of rupture. A nonuniform stress field, σ, can always be written in terms of the maximum stress in the following manner

$$\sigma(x,y,z) = Sf(x,y,z) \tag{2}$$

For a two-parameter Weibull model the risk of rupture is of the form

$$B(S) = A\left(\frac{S}{S_o}\right)^{\alpha} \quad (S_o, \alpha > 0) \tag{3}$$

where

$$A = \int_V [f(x,y,z)]^{\alpha} dV \tag{4}$$

and S_0 is the scale parameter, sometimes referred to as the characteristic strength, and α is the shape parameter which characterizes the flaw distribution in the material. Both of these parameters are considered to be material properties independent of size. Thus, the risk to break will be a function of the stress distribution in the test specimen.

Equation 3 can also be written in the form

$$B(S) = \left(\frac{S}{S_A}\right)^{\alpha} \tag{5}$$

where

$$S_A = S_o A^{-1/\alpha} \tag{6}$$

and the probability of survival (Equation 1) can be written as a two-parameter Weibull distribution

$$R(S) = \exp\left[-\left(\frac{S}{S_A}\right)^{\alpha}\right] \tag{7}$$

Thus, tensile tests from specimens containing different stress fields can be represented by a two-parameter Weibull distribution with the same shape parameter, but with a scale parameter which will shift according to Equation 6.

For the case of a simple tensile test under uniform stress, Equation 6 takes the form

$$S_A = S_t = S_o(V_t)^{-1/\alpha} \tag{8}$$

where the subscript t denotes simple tension. Thus, the scale parameter for uniform tension is a function of specimen volume.

For flexural loading the integration in Equation 4 can be performed in closed form and results in the following relationships between the scale parameters for tension and flexure

$$\frac{S_b}{S_t} = \left[2(\alpha+1)^2\left(\frac{V_t}{V_b}\right)\right]^{1/\alpha} \quad \text{(3-point)} \tag{9}$$

$$\frac{S_b}{S_t} = \left[\frac{4(\alpha+1)^2}{(\alpha+2)}\left(\frac{V_t}{V_b}\right)\right]^{1/\alpha} \quad \text{(4-Point)} \tag{10}$$

where the subscript b denotes bending. The results for 4-point flexure correspond to loading at quarter points. In order to illustrate the effect of nonuniform stress distribution, consider the case $V_t = V_b$. For values of α = 15 and 25, Equations 9 and 10 yield

$$\frac{S_b}{S_t} = \begin{cases} 1.52, & \alpha = 15 \\ 1.33, & \alpha = 25 \end{cases} \qquad \text{(3-Point)} \tag{11}$$

$$\frac{S_b}{S_t} = \begin{cases} 1.31, & \alpha = 15 \\ 1.20, & \alpha = 25 \end{cases} \qquad \text{(4-Point)} \tag{12}$$

These values of α are typical of currently utilized composites such as glass-epoxy and graphite-epoxy. Thus, the flexure test can, in theory, produce significantly higher tensile strengths than the tensile test, with the 3-point loading producing the highest strength. This is due to the fact that the maximum stress is produced at the outer surface in the center of the beam, while the 4-point loading produces the maximum stress at the outer surface throughout the center section. In particular, the smaller the volume under maximum stress, the higher the local strength.

It should be noted that Equations 9 and 10 are based on the assumption that failure in the flexure test is a direct function of normal stress on the tension side of the beam. The effect of interlaminar shear and normal stresses are completely neglected.

Specimen thickness effects as well as stress gradient effects are also of interest. For pure tension, Equation 8 becomes

$$S_t = S_o(Lbh)^{-1/\alpha} \tag{13}$$

where L, b, and h are gage length, width, and thickness, respectively, of the tensile coupon. For specimens of thickness h_1 and h_2, Equation 13 becomes

$$\frac{S_{t1}}{S_{t2}} = \left(\frac{h_2}{h_1}\right)^{1/\alpha}, \quad h_2 > h_1 \tag{14}$$

Thus, the thin specimens will have a higher characteristic strength compared to the thick specimens. In the case of flexural loading the beam span, L, must also be adjusted for any thickness change in order to assure a constant span-to-depth ratio in the flexure test. For 3-point loading, Equation 8 becomes

$$S_b = S_o \left[\frac{2(\alpha+1)^2}{bh^2} \left(\frac{h}{L} \right) \right]^{1/\alpha} \quad \text{(3-Point)} \tag{15}$$

For specimens of thickness h_1 and h_2, with L/h constant, Equation 15 yields

$$\frac{S_{b1}}{S_{b2}} = \left(\frac{h_2}{h_1} \right)^{2/\alpha}, \qquad h_2 > h_1 \tag{16}$$

Because of the requirement for a constant L/h ratio, any thickness change will have greater effect on the flexure test than on the tensile coupon test. Again, thin specimens should yield a higher characteristic strength than thick specimens. It is also obvious that Equation 16 holds for 4-point bending as well as 3-point bending.

SECTION III

EXPERIMENTAL PROCEDURE AND DATA REDUCTION

Two graphite-epoxy material systems were chosen for this investigation, T300/5208 (Narmco) and AS/3501-5A (Hercules). Unidirectional panels were fabricated in an autoclave according to each manufacturer's recommended cure cycle. The average fiber volume content was 70 percent for T300/5208 and 65 percent for AS/3501-5A. Both 8 ply and 16 ply panels were processed for T300/5208, while only 16 ply panels were fabricated for AS/3501-5A. Test specimens were cut from the large panels with a diamond wheel.

Specimen geometry and dimensions for both tension and flexure are shown in Figure 1. For tension a straight sided coupon was utilized in accordance with ASTM Standard D-3039 (Reference 6). The flexure tests were run in accordance with ASTM Standard D-790 (Reference 7) with the following deviations. Loads were applied at a distance of L/4 from the supports, rather than at a distance of L/3 as required by the ASTM standard. In addition, the specimens were 13mm (0.5 in) wide rather than 25mm (1.0 in). These deviations have become accepted practice for graphite-epoxy composites. A test matrix is shown in Table 1.

Let m be the number of conditions tested (tension, 3 pt. flexure, specimen thickness, etc.) and n_i the number of specimens tested under the i-th condition, which leads to the data sets

$$S_i(S_{i1}, S_{i2}, \ldots, S_{in_i}), \quad i = 1,2,\ldots,m \tag{17}$$

where S_{il} are the strengths of individual specimens. Each data set, S_i, was fitted to the two-parameter Weibull distribution

$$R(S_i) = \exp\left[-\left(\frac{S_i}{S_{oi}}\right)^{\alpha_i}\right] \tag{18}$$

The parameters α_i and S_{oi} were determined from the maximum likelihood estimator (MLE) which is of the form (Reference 8)

$$\frac{\sum_{j=1}^{n_i} S_{ij}^{\hat{\alpha}_i} \ln S_{ij}}{\sum_{n=1}^{n_i} S_{ij}^{\hat{\alpha}_i}} - \frac{1}{n_i} \sum_{j=1}^{n_i} S_{ij} - \frac{1}{\hat{\alpha}_i} = 0 \qquad (19)$$

$$\hat{S}_{oi} = \left(\frac{1}{n_i} \sum_{j=1}^{n_i} S_{ij}^{\hat{\alpha}_i} \right)^{1/\hat{\alpha}_i} \qquad (20)$$

where $\hat{\alpha}_i$ and $\hat{S}_{oi}$ denote estimated values of α_i and S_{oi}, respectively. Equation 19 has only one real positive root. As a result, an iterative scheme can be utilized until a value of $\hat{\alpha}_i$ is obtained to any desired number of decimal places. The resulting value of $\hat{\alpha}_i$ can then be used in conjunction with Equation 20 to obtain $\hat{S}_{oi}$.

Since the shape parameters, α_i, are based on a limited sample size, some variation in their estimated value, $\hat{\alpha}_i$, is anticipated even though they may be the same for tension and flexure as predicted by the Weibull Theory. A two sample test is available (Reference 9) which allows for testing the equality of shape parameters in two-parameter Weibull distributions with unknown scale parameters. The approach is based on MLE and the results depend on sample size and confidence level desired. Let $\hat{\alpha}_{max}$ and $\hat{\alpha}_{min}$ be the maximum and minimum values obtained for $\hat{\alpha}_i$. In order to use the tabulated information in Reference 9, it is necessary that $\hat{\alpha}_{max}$ and $\hat{\alpha}_{min}$ be associated with equal sample size, n. If $\hat{\alpha}_{max}$ and $\hat{\alpha}_{min}$ are from the same distribution, then it is expected that (Reference 9)

$$\frac{\hat{\alpha}_{max}}{\hat{\alpha}_{min}} < A(\gamma, n), \quad A > 1 \qquad (21)$$

for a given confidence level, γ, and sample size, n. Values of A tabulated from Reference 9 are shown in Table 2 for various sample sizes corresponding to a confidence level of 0.98. The large values of A associated with small sample sizes suggest that significant variations in $\hat{\alpha}_i$ are likely to be encountered with small data sets taken from the same population.

For cases where $\hat{\alpha}_{max}$ and $\hat{\alpha}_{min}$ satisfy Equation 21 a data pooling technique is necessary for determining a single value of α associated with all S_i. The data pooling approach utilized in the present report is based on the normalized data set (Reference 10)

$$X(X_{i1}, X_{i2}, \ldots, X_{in_i}), \quad i = 1, 2, \ldots, m \tag{22}$$

where

$$X_{ij} = \frac{S_{ij}}{\hat{S}_{oi}} \tag{23}$$

Thus, each data set included in the pooling procedure was normalized by its estimated characteristic strength and the resulting normalized data was fit to the pooled two-parameter Weibull distribution

$$R(X) = \exp\left[-\left(\frac{X}{X_o}\right)^{\hat{\alpha}_p}\right] \tag{24}$$

For the pooled Weibull distribution in Equation 20, the MLE relationship takes the form

$$\frac{\sum_{i=1}^{m}\sum_{j=1}^{n_i} X_{ij}^{\hat{\alpha}_p} \ln X_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n_i} X_{ij}^{\hat{\alpha}_p}} - \frac{1}{M}\sum_{i=1}^{m}\sum_{j=1}^{n_i} X_{ij} - \frac{1}{\hat{\alpha}_p} = 0 \tag{25}$$

where $\hat{\alpha}_p$ is the estimated value of α_p and

$$M = \sum_{i=1}^{m} n_i \tag{26}$$

It should be noted that MLE is asymptotically unbiased, i.e., it is a biased estimator for small sample sizes (Reference 3). Unbiasing factors are tabulated in Reference 11, which takes the form

$$\bar{\alpha}_p = \hat{\alpha}_p B(M), \quad B \leq 1 \tag{27}$$

where $\bar{\alpha}_p$ is the unbiased estimate of α_p and B is the unbiasing factor. The scale parameter for pooled distributions take the form

$$\bar{X}_o = \left(\frac{1}{M} \sum_{i=1}^{m} \sum_{j=1}^{n_i} X_{ij}^{\bar{\alpha}_p} \right)^{1/\bar{\alpha}_p} \tag{28}$$

where $\bar{X}_o$ is the estimate of X_o associated with the estimated unbiased shape parameter $\bar{\alpha}_p$.

For a perfect fit to the data pooling scheme, the location parameter, $\bar{X}_o$, should be unity. However the values of $\hat{S}_{oi}$ can be adjusted to produce an exact value of unity for $\bar{X}_o$. In particular,

$$\bar{S}_p = \bar{X}_o \hat{S}_{oi} \tag{29}$$

where $\bar{S}_p$ denotes estimated values of S_o associated with the adjusted two-parameter Weibull distribution

$$R(X) = \exp\left(-X^{\bar{\alpha}_p}\right) \tag{30}$$

Weibull parameters are shown in Table 3 for each data set. In order to use the two sample test results tabulated in Reference 9, it was necessary to reduce the number of replicates in some data sets so that equal sample sizes could be obtained within each material system. This was accomplished by numbering the failures in each data set to be reduced from lowest strength to highest strength and using a table of random numbers to discard the appropriate number of specimens. Weibull parameters were then determined from the reduced sets by use of MLE. The resulting shape parameters, α_i, represented estimates for equal sample sizes within each material system and Equation 17 in conjunction with the tabulated data from Reference 9 could then be applied. Weibull parameters associated with equal sample size sets are also shown in Table 3.

All of the strength data associated with each sample set is shown in Tables 4-11. Asterisks indicate specimens discarded for the purpose of obtaining data sets of equal sample size.

SECTION IV

DISCUSSION OF RESULTS

A cursory examination of the Weibull shape parameters in Table 3 shows that $\hat{\alpha}_{min}$ is associated with tensile coupon data for both material systems utilized. Application of the two sample tests (Equation 17) to all of the data within each material system failed to indicate a constant value of α_i. Application of the two sample tests to flexure data and tensile coupon data separately indicated that pooling procedures would be appropriate for each of these test methods. Since tensile coupon data on AS/3501-5A composites were obtained for only one specimen geometry, data pooling could only be accomplished on flexure strength for this material.

Comparison between strength data and Weibull distributions obtained from the data reduction procedures are shown in Figures 2-9. Data points are converted to probabilities of survival from the Median Rank (MR) defined as

$$MR = \frac{j - 0.3}{n + 0.4} \tag{31}$$

where j is the survival order number (data listed in decreasing order of strength) and n is the total number of samples tested. Pooled shape parameters are denoted by $\bar{\alpha}_t$ and $\bar{\alpha}_b$ where the subscripts t and b denote tension and bending, respectively.

Note that for both graphite-epoxy material systems the ratio of bending shape parameters to tension shape parameters, $\bar{\alpha}_b/\bar{\alpha}_t$, is approximately 2, which is a departure from classical Weibull Theory. The characteristic flexure strengths are consistently higher than the characteristic tensile strengths as predicted by the Weibull failure model.

The difference obtained in shape parameters between tensile coupons and flexure tests suggests that their failures are governed by two different flaw distributions. Typical failure modes, which are illustrated in Figure 10 for tension and Figure 11 for flexure, demonstrate the same brooming type of failure mode for both loading methods. Tension tends to produce a more catastrophic failure due to the uniform stress field, while flexure loading produces a more localized failure due to stress gradients. Similar modes could lead one to believe that the failures are governed by the same flaw distribution. This can, however, be misleading as further discussion will show.

Composite panels are constructed by stacking layers of unidirectional prepreg tape in the desired orientations and curing the resulting sheet. The prepreg tape is usually manufactured in 3-inch or 12-inch widths. Thus, large panels require the tape to be spliced by laying strips of the prepreg material side by side. Some specimens cut from such a panel will contain splices while others will not. Such splices, when occurring in 0 degree plies, can cause a reduction in tensile strength (Reference 11). As a result, the splices represent a characteristic flaw which is not present in all specimens. Tensile coupon data becomes more sensitive to splices because of uniform load, while the stress gradient characteristic of flexure specimens renders them less sensitive to splices. In particular, even if a flexure specimen contains a splice, the probability of it occurring at the point of maximum stress is small. Thus, tensile coupon data may have an apparently higher scatter than flexure data due to the presence of splices in some specimens.

Another source of apparent scatter in tensile coupon data is specimen misalignment which induces bending and/or a nonuniform stress field. The straight sided geometry associated with composite tensile coupons makes them particularly sensitive to misalignment, with unidirectional composites being the most sensitive due to the high ratio of axial to transverse strength and stiffness. It can be easily seen from Equations 3 and 4 that a constant nonuniform stress field will change the characteristic strength but not the shape parameter. Misalignment, however, is likely to induce a nonuniform stress field which varies from specimen to specimen depending on the degree and nature of the misalignment. Such variations can reduce the estimated value of the shape parameter, $\hat{\alpha}_i$, by producing artificially large scatter in measured tensile strengths.

Another anomaly associated with the experimental data is the extremely high tensile strength values obtained from 3-point flexural loading of 8 ply T300/5208 unidirectional composites. It is possible that the ratio of load nose radius-to-specimen thickness is too large, producing a distributed load rather than a concentrated load.

SECTION V

CONCLUSIONS

It is obvious from the data presented that the experimental results do not correlate with a two-parameter Weibull statistical failure model. As pointed out previously this lack of correlation may well be a result of test methodology and/or physical failure processes occurring in unidirectional composites. It is important from a design standpoint to establish if either the tensile coupon method or the flexure method reflect actual material variations. This can only be accomplished by establishing failure mechanisms and then relating them to the method of load introduction utilized by the test methods. Until this is done, it appears that any attempt to predict tensile coupon data from flexural data for design purposes is premature.

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TABLE 1

TEST MATRIX

Material	Tension	4-PT Flex	3-PT Flex
T300/5208, 8 Ply	25	---	28
T300/5208, 16 Ply	20	21	25
AS/3501-5, 16 Ply	36	30	28

TABLE 2

VALUES OF TWO SAMPLE TEST PARAMETERS, $\gamma = 0.98$
(REFERENCE 9)

n_i	A
5	3.550
10	2.213
15	1.870
20	1.703
100	1.266

TABLE 3

WEIBULL PARAMETERS

Test	T300/5208, 8Ply $\hat{S}_i$, MPa (kSI)	$\hat{\alpha}_i$	T300/5208, 16Ply $\hat{S}_{oi}$, MPa (kSI)	$\hat{\alpha}_i$	AS/3501-5, 16Ply $\hat{S}_{oi}$, MPa (kSI)	$\hat{\alpha}_i$
Tension	1790 (259)	17.7	1665 (241)	18.5	1506 (218)	13.3
Tension*	1776 (257)	20.4	-----	--	-----	--
Tension**	-----	--	-----	--	1506 (218)	13.2
4-Pt Flex	-----	--	1734 (251)	29.3	1624 (235)	29.2
4-Pt Flex	-----	--	1741 (252)	28.7	-----	--
4-Pt Flex	-----	--	-----	--	1624 (235)	32.7
3-Pt Flex	2377 (344)	41.4	1790 (259)	36.7	1617 (234)	22.9
3-Pt Flex*	2377 (344)	42.6	1797 (260)	36.2	-----	--

*Based on a reduced sample size of 20

**Based on a reduced sample size of 28

TABLE 4

TENSION DATA

T300/5208, 8 Ply, n_i = 25

S, MPa (kSI)
*1949 (282)
*1886 (273)
1886 (273)
1873 (271)
*1859 (269)
1817 (263)
1810 (262)
1797 (260)
1797 (260)
1783 (258)
1783 (258)
1769 (256)
1755 (254)
1748 (253)
1748 (253)
1741 (252)
1721 (249)
*1721 (249)
1679 (243)
1631 (236)
1624 (234)
*1610 (233)
1575 (228)
1472 (213)
1451 (210)

*Specimens eliminated for two sample tests.

TABLE 5

TENSION DATA

T300/5208, 16 Ply, n_i = 20

S, MPa (kSI)
1762 (255)
1741 (252)
1734 (251)
1714 (248)
1693 (245)
1679 (243)
1679 (243)
1679 (243)
1665 (241)
1658 (240)
1638 (237)
1617 (234)
1610 (233)
1582 (229)
1582 (229)
1575 (228)
1513 (219)
1479 (214)
1430 (207)
1423 (206)

TABLE 6

4-POINT FLEXURE DATA

T300/5208, 16 Ply, n_i = 21

S, MPa (kSI)
1831 (265)
1810 (262)
1762 (255)
1755 (254)
1755 (254)
1755 (254)
1755 (254)
*1748 (253)
1748 (253)
1741 (252)
1734 (251)
1728 (250)
1721 (249)
1721 (249)
1700 (246)
1693 (245)
1638 (237)
1631 (236)
1631 (236)
1610 (233)
1596 (231)
1589 (230)

*Specimens eliminated for two sample tests.

TABLE 7

3-POINT FLEXURE DATA

T300/5208, 8 Ply, n_i = 28

S, MPa (kSI)
2446 (354)
*2432 (352)
2425 (351)
2419 (350)
*2419 (350)
2419 (350)
2412 (349)
2384 (345)
*2384 (345)
2377 (344)
2377 (344)
2370 (343)
2363 (342)
2356 (341)
2349 (340)
*2349 (340)
2342 (339)
*2322 (336)
*2308 (334)
2308 (334)
2301 (333)
*2294 (332)
2287 (331)
2273 (329)
2266 (328)
2204 (319)
2204 (319)
*2177 (315)

*Specimens eliminated for two sample tests.

TABLE 8

3-POINT FLEXURE DATA

T300/5208, 16 Ply, n_i = 25

S, MPa (kSI)
1893 (274)
1817 (263)
1817 (263)
*1810 (262)
1804 (261)
1797 (260)
1790 (259)
1790 (259)
*1783 (258)
1776 (257)
1776 (257)
1776 (257)
1762 (255)
1762 (255)
1762 (255)
*1755 (254)
1755 (254)
1755 (254)
1748 (253)
*1748 (253)
1734 (251)
1721 (249)
1721 (249)
1714 (248)
*1686 (244)

*Specimens eliminated for two sample tests.

TABLE 9

TENSION DATA

AS/3501-5A, 16 Ply, $n_i = 36$

S, MPa (kSI)
1686 (244)
1645 (238)
*1638 (237)
1617 (234)
1562 (226)
1562 (226)
1555 (225)
1555 (225)
1548 (224)
1541 (223)
1520 (220)
1520 (220)
1506 (218)
*1506 (218)
*1499 (217)
1479 (214)
1472 (213)
1458 (211)
1444 (209)
*1437 (208)
*1430 (207)
1423 (206)
*1410 (204)
1410 (204)
1389 (201)
cont'd

*Specimens eliminated for two sample tests.

TABLE 9 (Cont'd)

TENSION DATA

AS/3501-5A, 16 Ply, n_i = 36

S, MPa (kSI)
1382 (200)
1382 (200)
1368 (198)
1354 (196)
1354 (196)
1354 (196)
1347 (195)
*1285 (186)
*1271 (184)
1099 (159)
1050 (152)

*Specimens eliminated for two sample tests.

TABLE 10

4-POINT FLEXURE DATA

AS/3501-5A, 16 Ply, n = 30

S, MPa (kSI)
*1721 (249)
1700 (246)
1686 (244)
1665 (241)
1658 (240)
1651 (239)
1651 (239)
1645 (238)
1631 (236)
1631 (236)
1617 (234)
1610 (233)
1610 (233)
1603 (232)
1596 (231)
1596 (231)
1596 (231)
1582 (229)
1569 (227)
1569 (227)
1562 (226)
1562 (226)
1555 (225)
1555 (225)
*1548 (224)
1548 (224)
1534 (222)
1527 (221)
1513 (219)
1479 (214)

*Specimens eliminated for two sample tests.

TABLE 11

3-POINT FLEXURE DATA

AS/3501-5A, 16 Ply, n_i = 28

S, MPa (kSI)
1714 (248)
1707 (247)
1679 (243)
1672 (242)
1672 (242)
1651 (239)
1651 (239)
1638 (237)
1631 (236)
1617 (234)
1610 (233)
1610 (233)
1596 (231)
1596 (231)
1589 (230)
1575 (228)
1541 (223)
1527 (221)
1527 (221)
1527 (221)
1520 (220)
1513 (219)
1513 (219)
1506 (218)
1499 (217)
1472 (213)
1444 (209)
1423 (206)

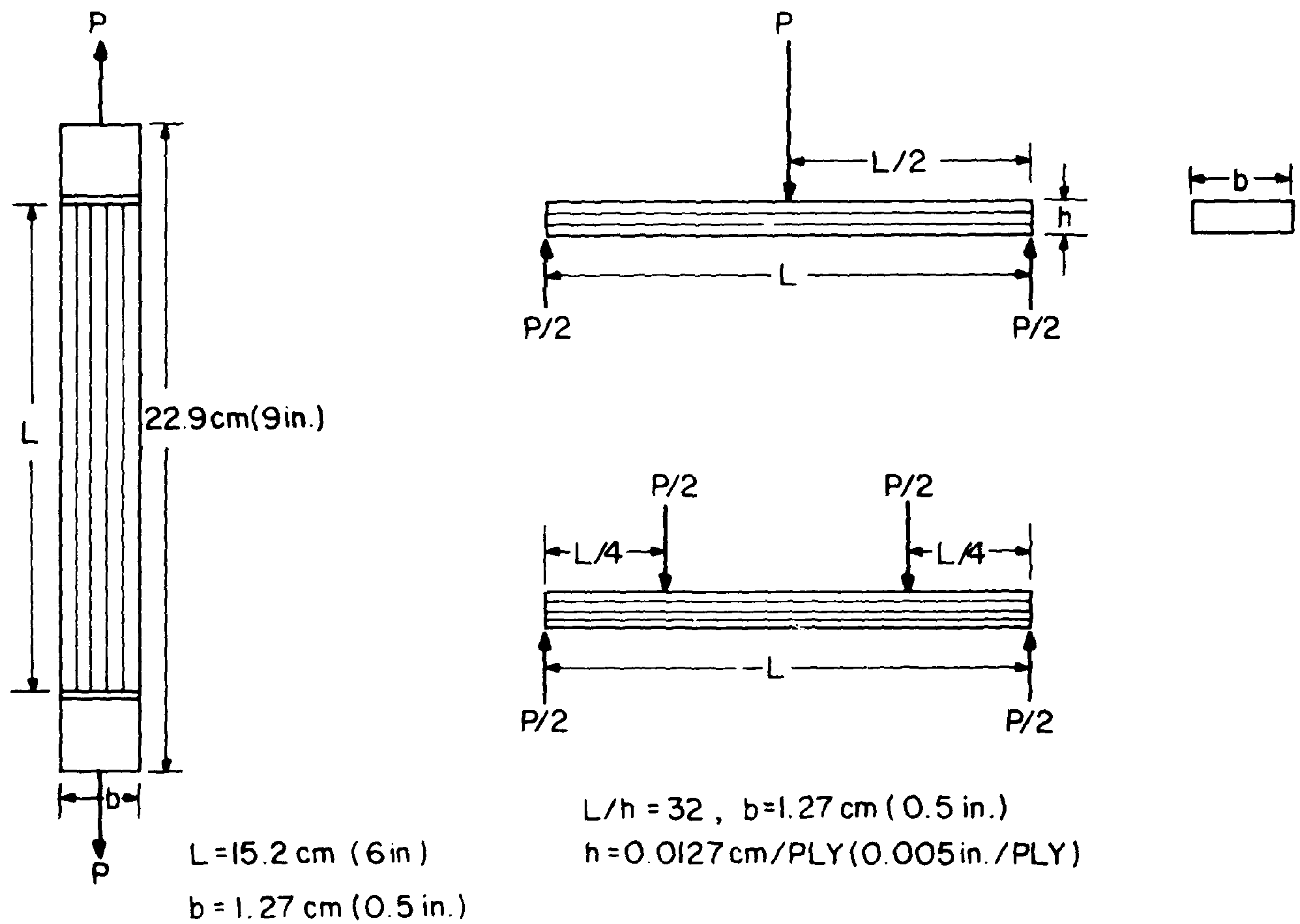

Figure 1. Geometry of Test Specimens.

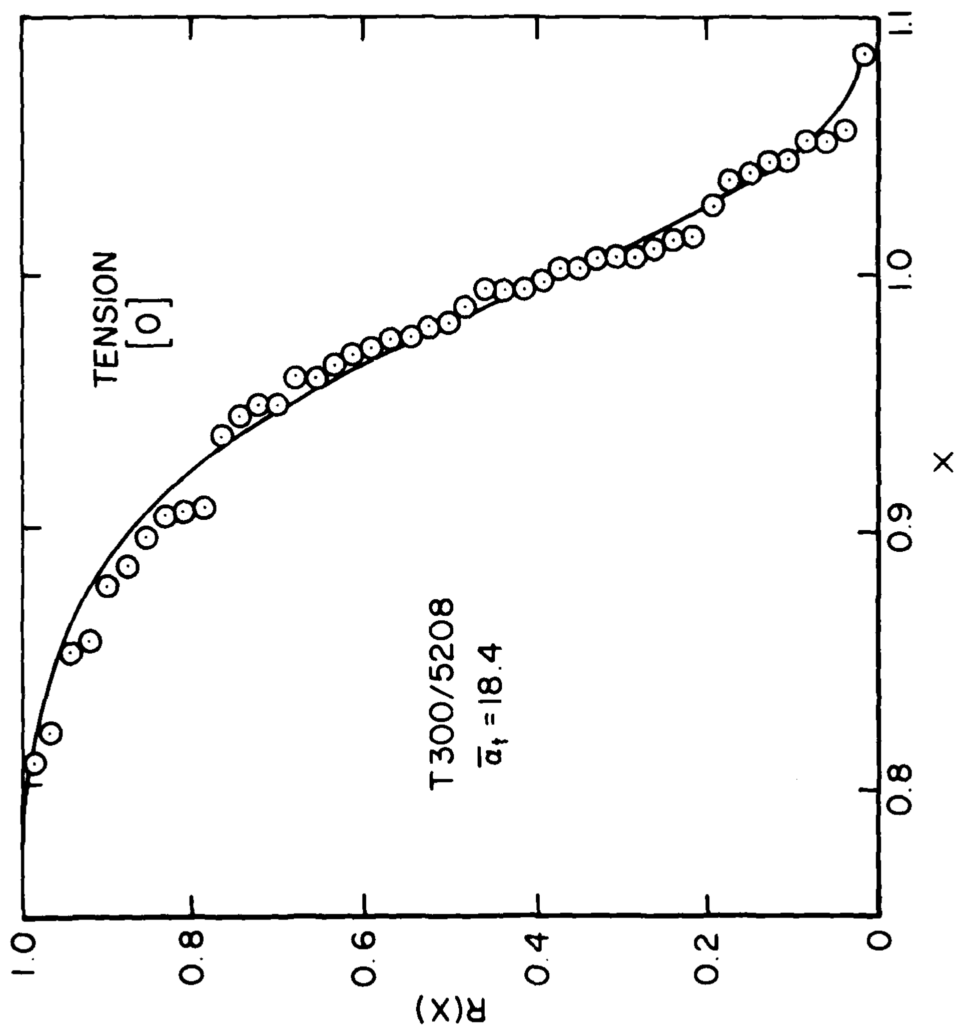

Figure 2. Pooled Weibull Distribution for Tension Loading, T300/5208 Graphite-Epoxy Composites.

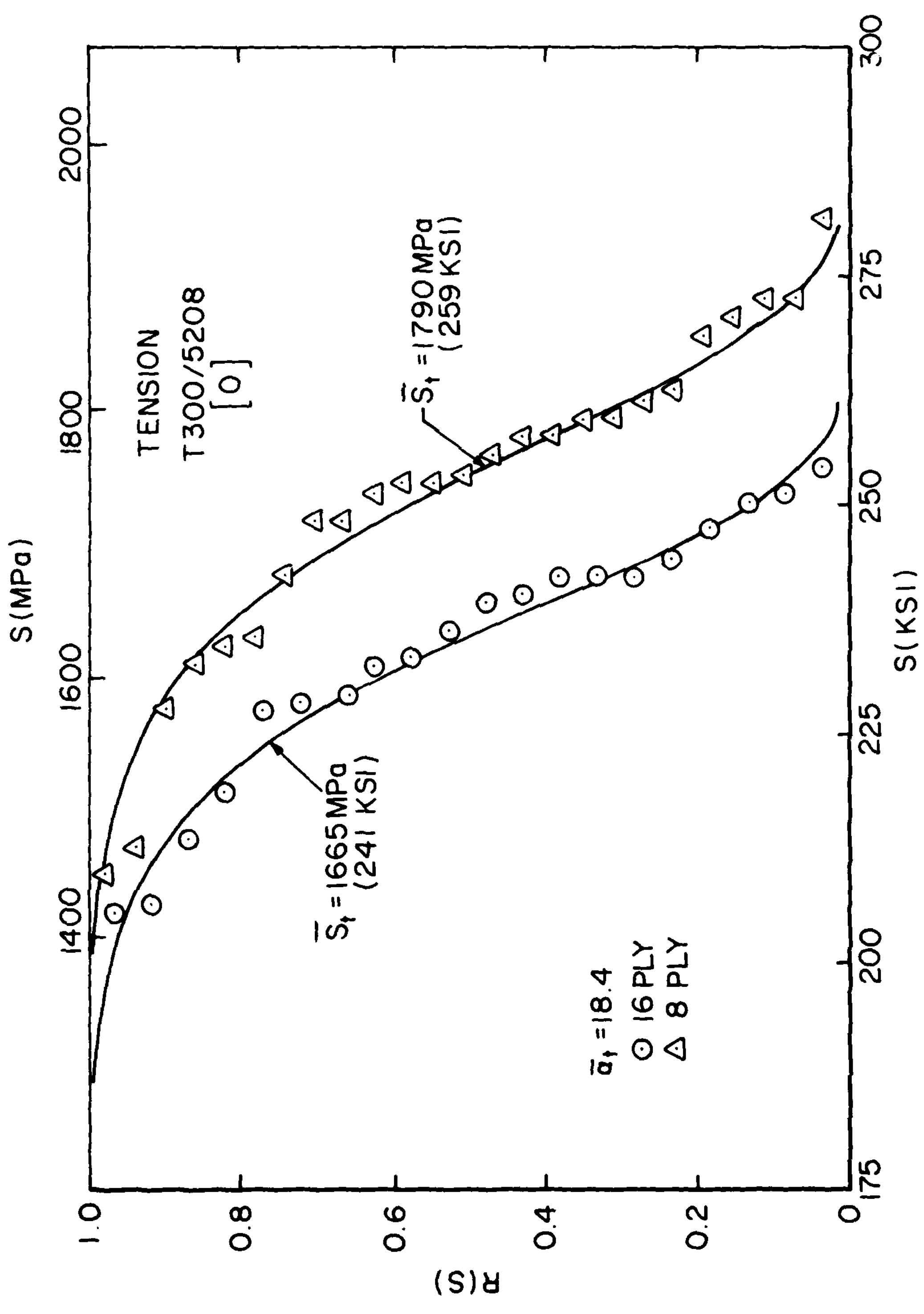

Figure 3. Weibull Distributions for Tension Loading, T300/5208 Graphite-Epoxy Composites.

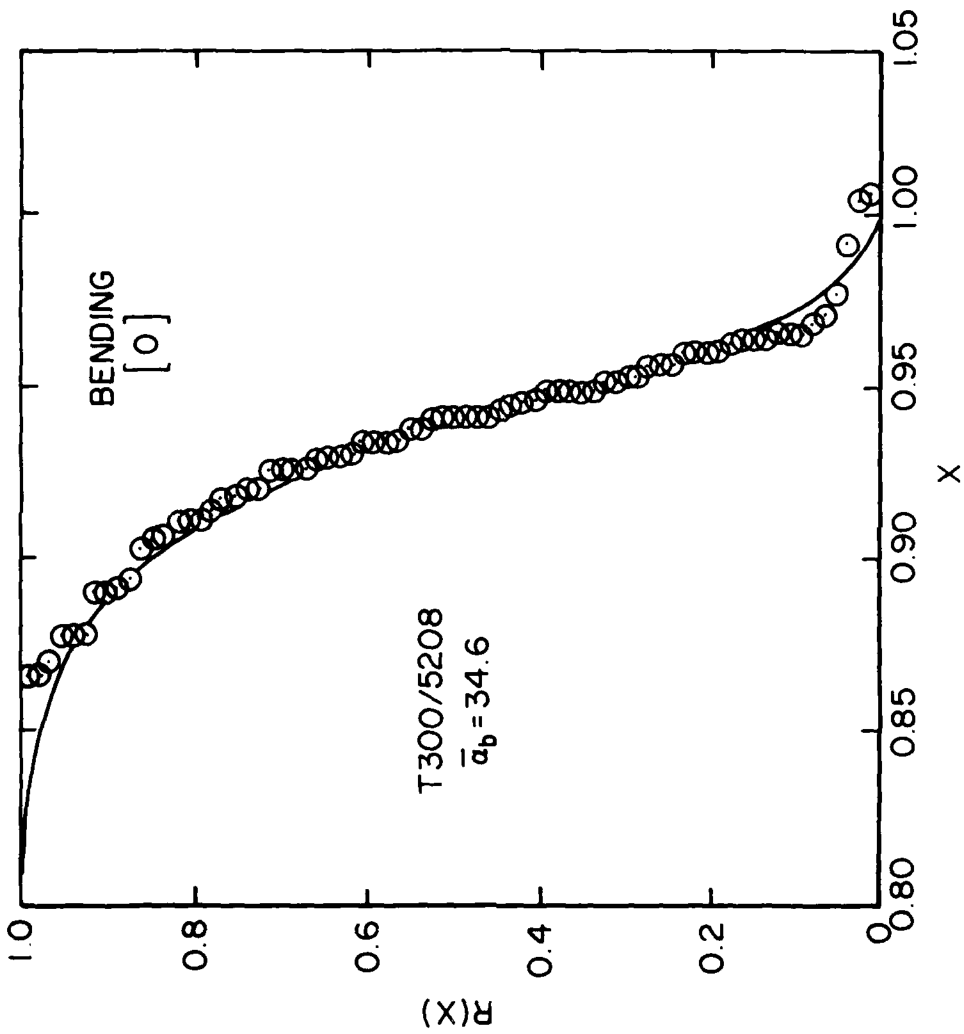

Figure 4. Pooled Weibull Distribution for Flexural Loading, T300/5208 Graphite-Epoxy Composites.

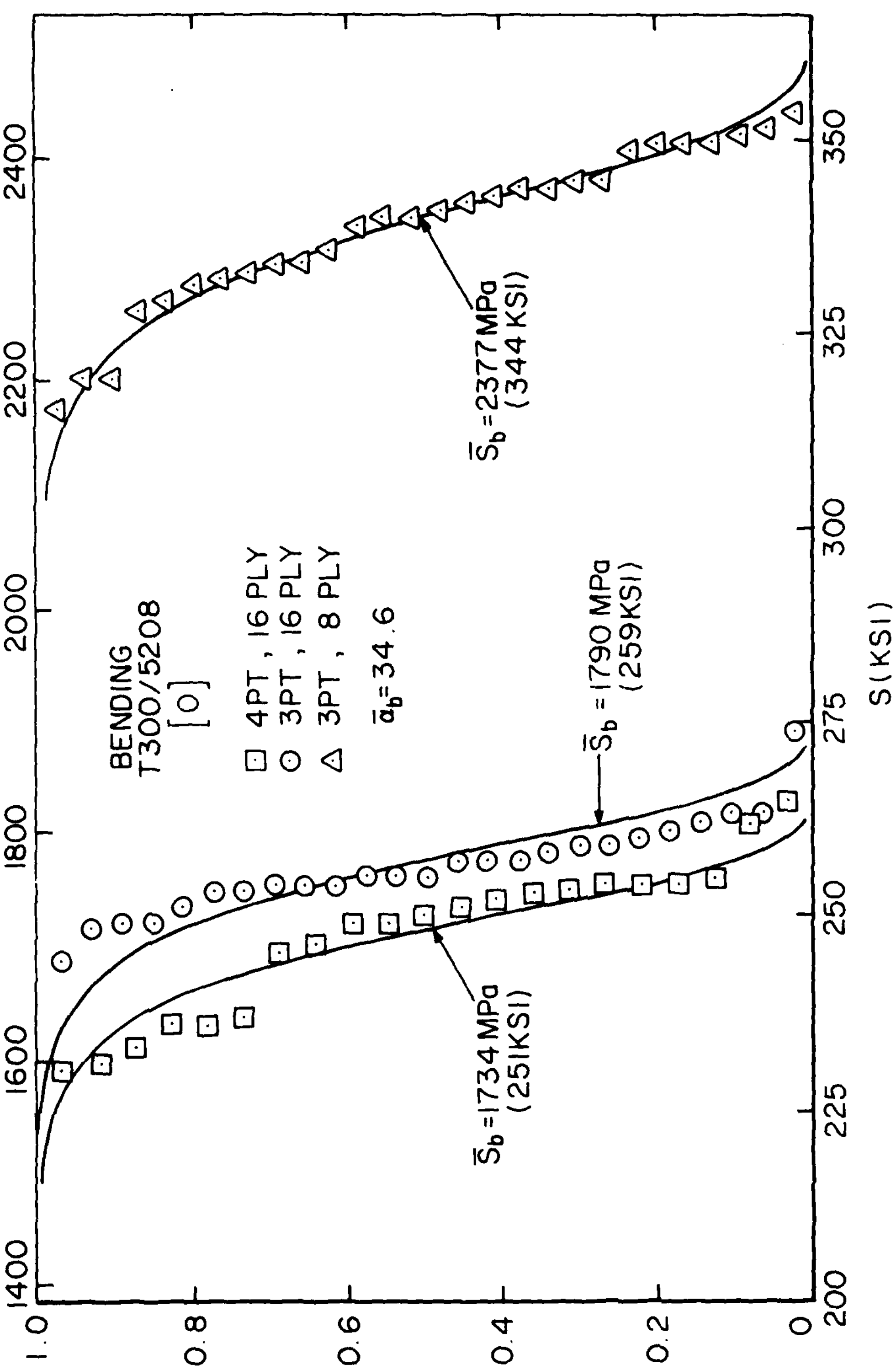

Figure 5. Weibull Distributions for Flexural Loading, *T300/5208 Graphite-Epoxy Composites.*

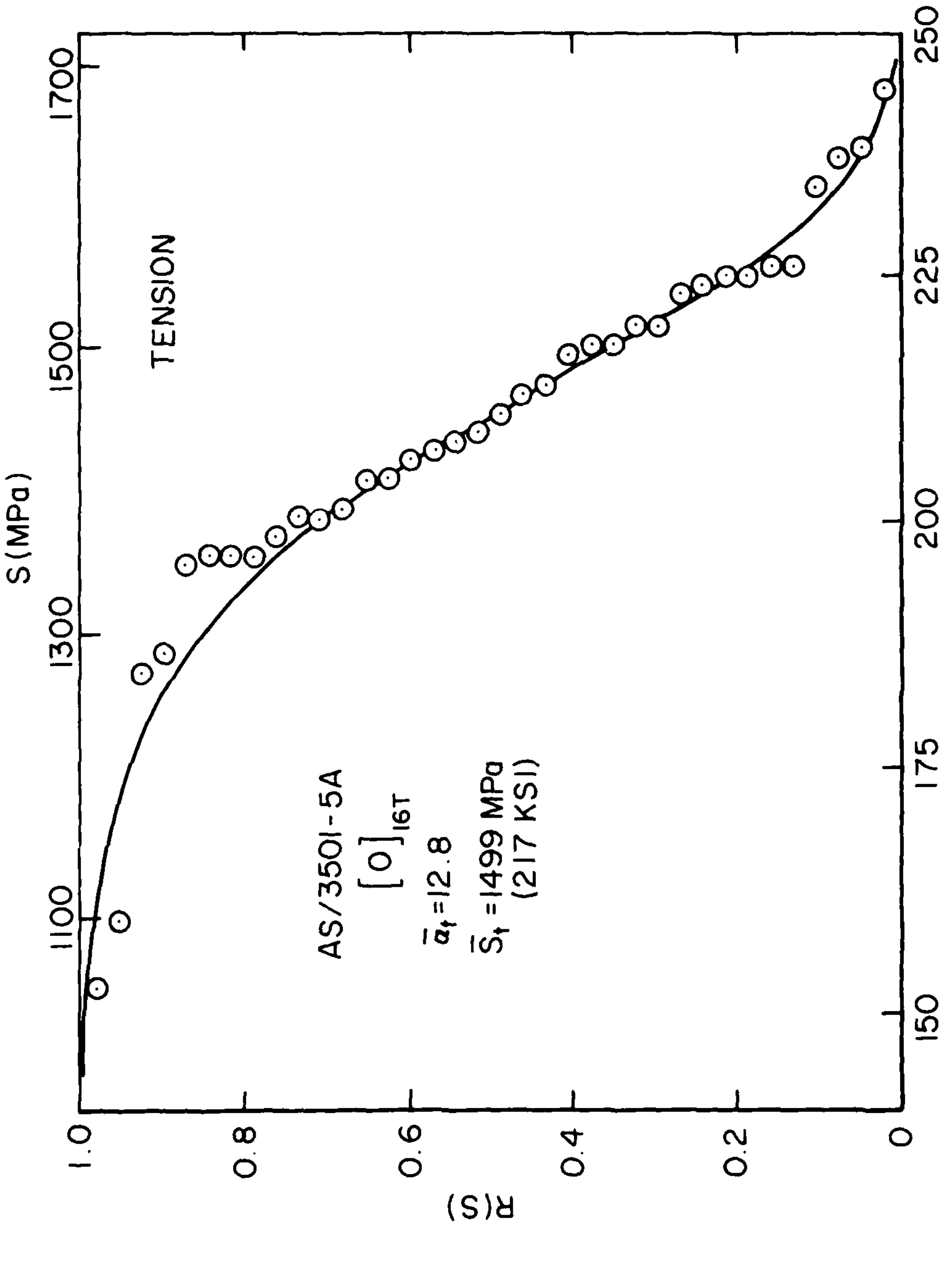

Figure 6. Weibull Distribution for Tension Loading, AS/3501-5A Graphite-Epoxy Composites.

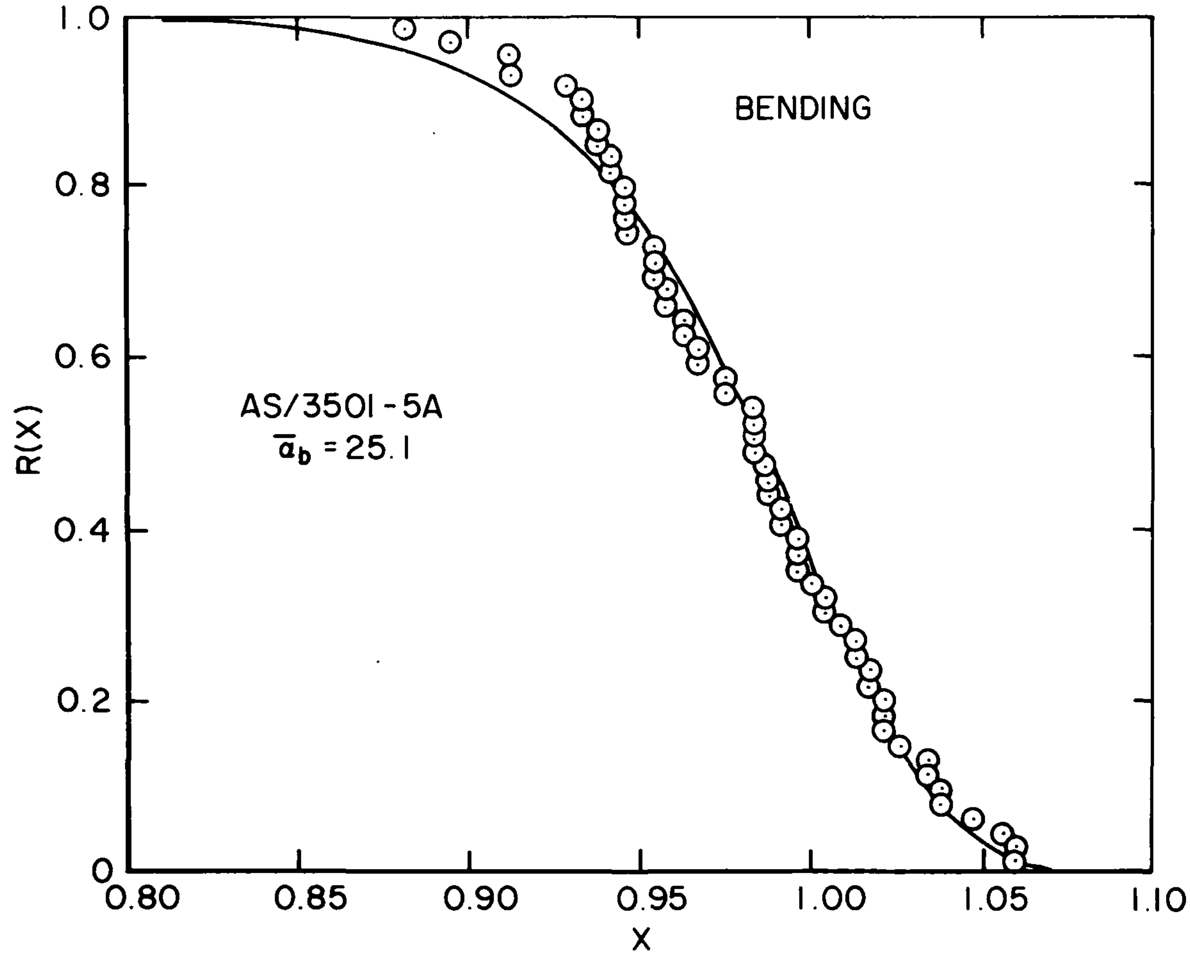

Figure 7. Pooled Weibull Distribution for Flexural Loading, AS/3501-5A Graphite-Epoxy Composites.

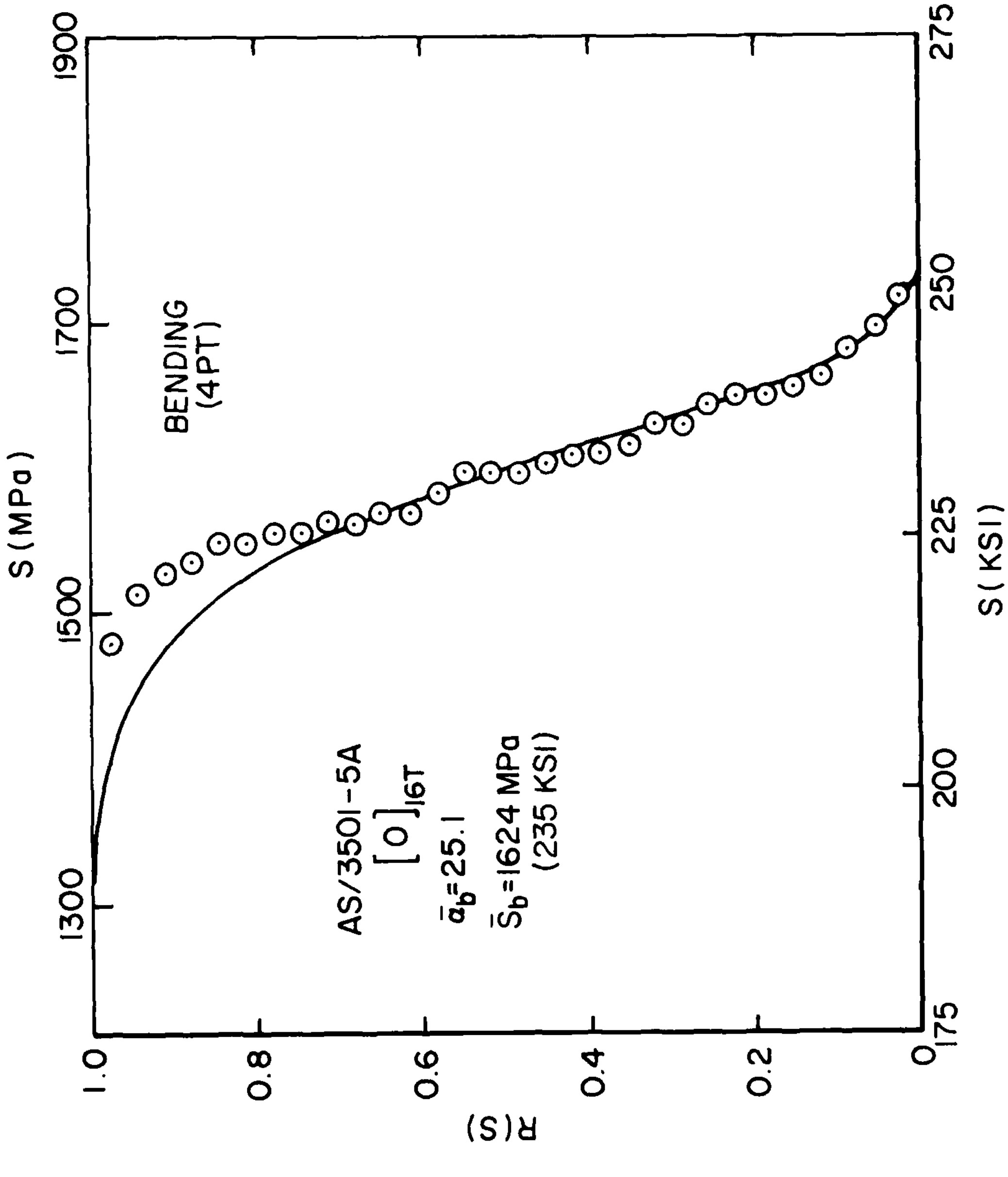

Figure 8. Weibull Distribution for 4-Point Flexural Loading, AS/3501-5A Graphite-Epoxy Composites.

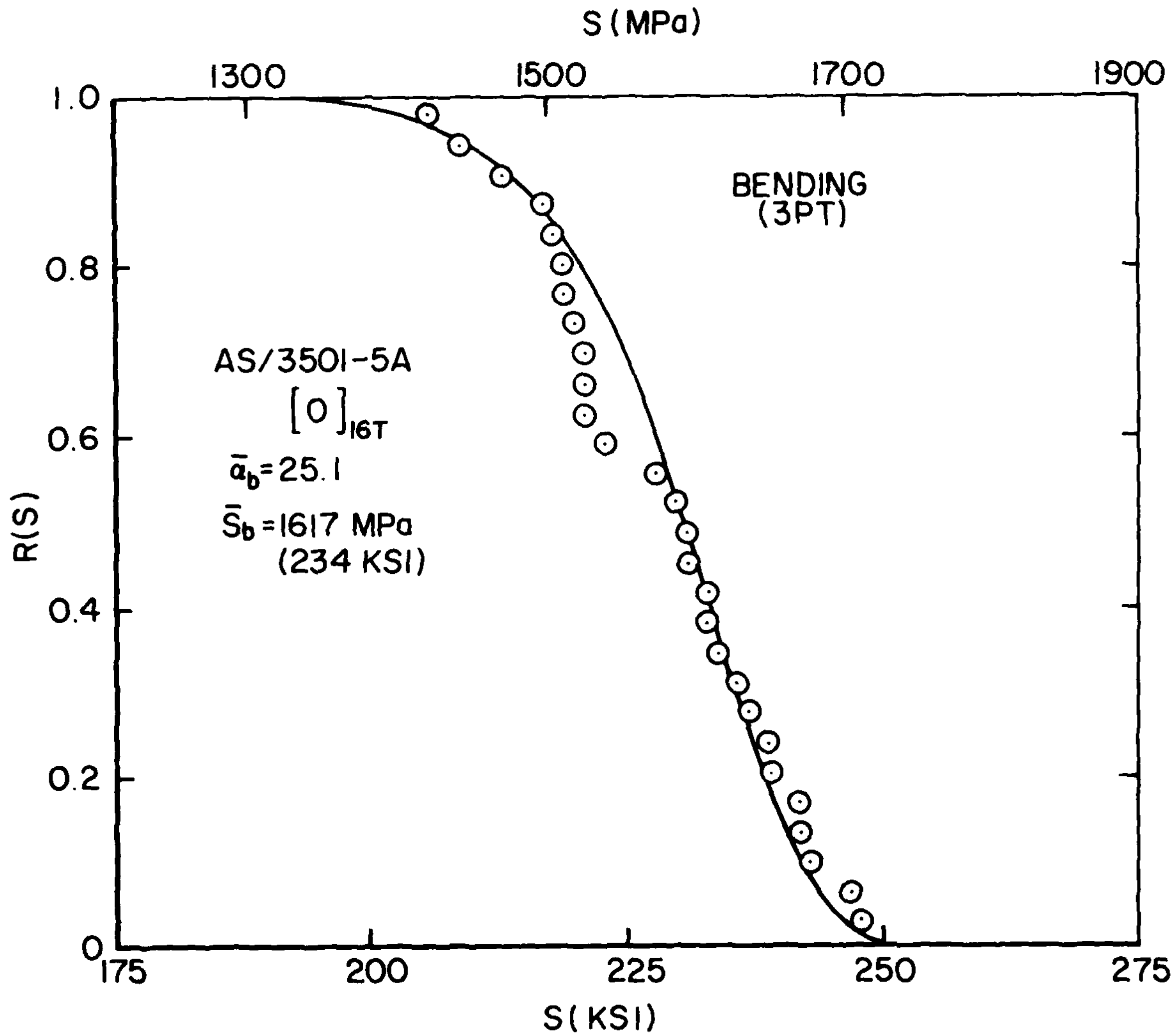

Figure 9. Weibull Distribution for 3-Point Flexural Loading, AS/3501-5A Graphite-Epoxy Composites.

Figure 10. Typical Tensile Coupon Failure.

Figure 11. Typical Bending Failure.

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